Smart Airport Pavement Instrumentation and Health Monitoring

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Outline

- Introduction
- Health Monitoring of Pavements
  - Needs
  - Methodology
  - Case Studies at ISU
- Conceptual Framework of Smart Airport Pavement Health Monitoring
- Summary

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Introduction

- Foreign Object Debris (FOD)
  - Considered to cause aircraft damage during its operation on airport runway

- Sources of FOD
  - Pavement distress
  - Aircraft parts
  - Ground vehicle parts
  - Stone and garbage
  - Wild animals

Introduction

- Airport pavements
  - Higher load magnitudes and tire pressures from airplanes
  - Lower load repetitions
- Highway pavements
  - Lower load magnitudes and tire pressures from vehicles
  - Higher load repetitions

(FAA Advisory Circular AC 150/5100-13B, 2011)

Introduction

- Airfield pavement is prone to have deterioration from traffic and environmental loads
  - Predominately manifests the environmental load-related distresses rather than traffic load-related ones
  - Compared to highway pavements, more attention is needed to characterize environmental load and the associated pavement response/distress

(FAA Advisory Circular AC 150/5100-13B, 2011)

Introduction

- Common environmental load-related airport pavement distress types

Pavement Type	Rigid Pavement	Flexible Pavement
Environmental load related distress	• Blowup • Durability (“D”) Cracking • Popouts	• Thermal Cracking • Block Cracking

(Lary, 2009)

Introduction

- Blowup on airport runways is very dangerous for aircraft operations needing immediate attention

Ankeny Regional Airport, IA, 2011

(Photo courtesy of Snyder & Associates, Inc./Polk County Aviation Authority)

Introduction

Ankeny Regional Airport, IA, 2011

(Photo courtesy of Snyder & Associates, Inc./Polk County Aviation Authority)

Introduction



Muscatine Municipal Airport, IA, 2013

(Photo courtesy of Mike Mar)

Introduction

Guthrie County Regional Airport, IA, 2014

(Photo courtesy of Mike Mar)

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Needs

- To maintain safe pavement surfaces
  - Minimize FOD potential
  - Improve skid resistance

- To achieve sustainable pavement systems
  - Prevent load and climate induced distresses
  - Minimize water infiltration into pavement structure

- To correct existing defects

How to Conduct ?

- Smart sensor
  - Micro-Electromechanical Systems (MEMS)/ Nano-Electromechanical Systems (NEMS) technologies based sensors
- Wireless sensor network
- Electro-optical (EO) sensing

Smart Sensor

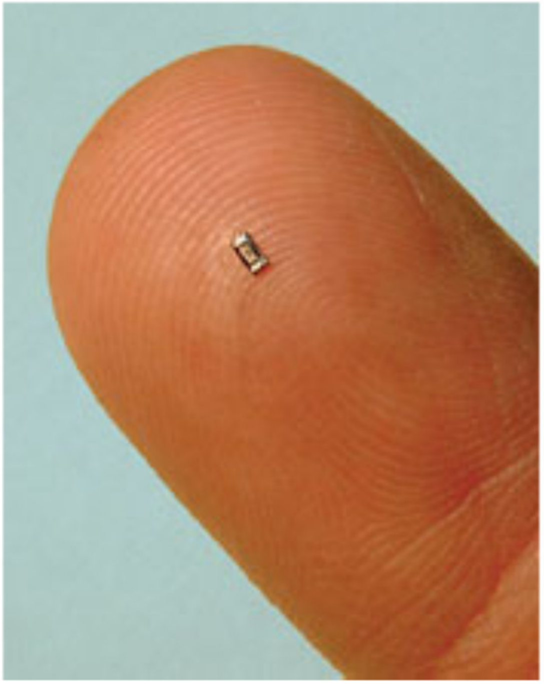
- Advantages
  - On-board Central-Processing- Unit (CPU)
  - Small size
  - Wireless
  - Low-cost

- MEMS (Micro-Electromechanical Systems)
  - Potential for ubiquitous sensing

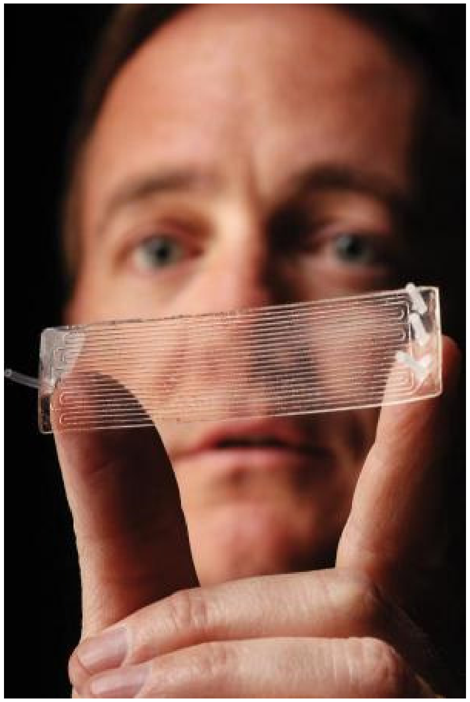
What is MEMS ?

- Miniature sensing devices
  - Interact with other environments to either obtain information or alter it
- Three broad categories
  - Sensors, actuators, and passive structures
- Smart materials and structures technology
  - Condition/health monitoring
  - Integrity/damage assessment
  - Structural control and repair

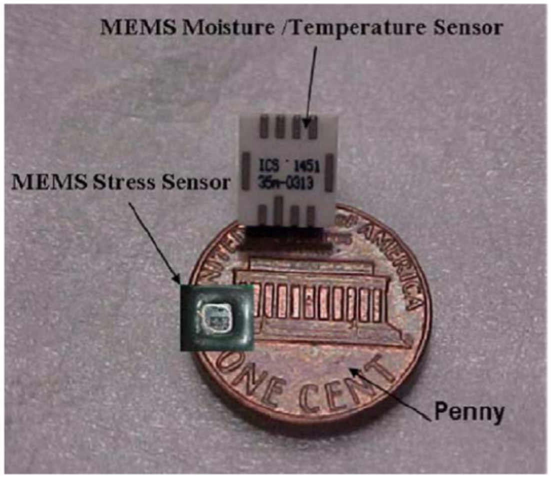
What is MEMS ?



Advanced Design Consulting USA, Inc

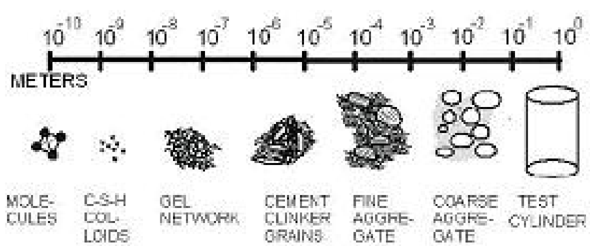


Sandia National Labs (2007)



Saafi and Romine (2005)

MEMS-based Civil Infrastructure Applications



Livingston (2005)

- MEMS-based Civil Infrastructure Applications
  - Asphalt Pavements
    - Lab Resilient Modulus
    - Pavement Roughness
    - Temperature
    - Moisture
    - Weigh-In-Motion (WIM)
    - Localized Strains
  - Concrete Pavements and Bridges
    - Temperature
    - Moisture
    - pH
    - Cl, Na, K ions
    - Carbonation and Leaching
    - ASR
    - WIM
    - Shrinkage Stress
    - Microcrack
    - Corrosion
    - Roughness
  - Geo-foundation
    - Moisture
    - Large Scale Strains
    - Geotextile Performance

Wireless Sensor Network

- Key issues
  - Hardware architecture
  - Require novel architectures and modes of operation
  - Finite energy sources used to power devices in the field
  - Signal disturbance to airplane

Wireless Sensor Network

- Comparison of wireless technologies available for sensor systems

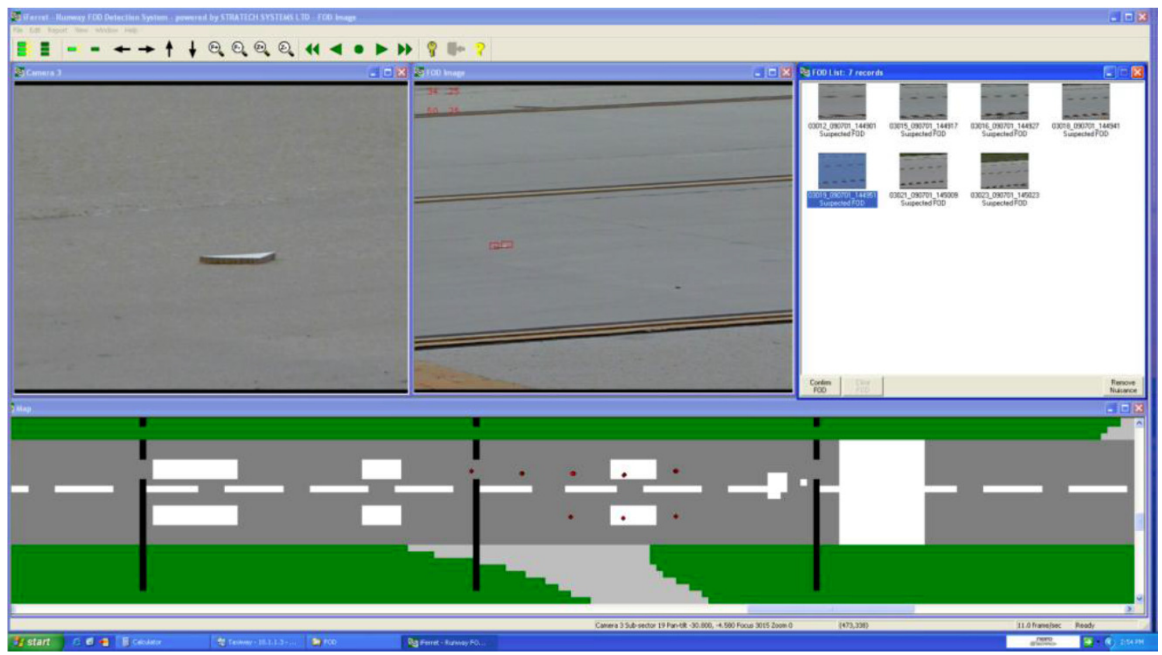
Aspects		Score (0 to 10)			
Factors	Weight	Bluetooth®	ZigBee®	Wifi®	Cellular
Multi-node network support	100	5	10	10	10
Throughput	60	7	6	8	3
Data rate	60	7	6	10	10
Range	50	6	5	7	10
Ease of implementation	50	6	8	6	4
Power consumption	-80	6	2	8	6
Cost	-100	5	3	7	8
Total Score		460	910	390	200

(Al-Khatib et al. 2006)

Electro-optical (EO) sensing

- Stratech iFerret™ electro optical system
  - A study of performance assessment has been conducted by Dr. Edwin E. Herricks at UIUC

(Photo courtesy of Dr. Edwin E. Herricks)



(Grave 2012)

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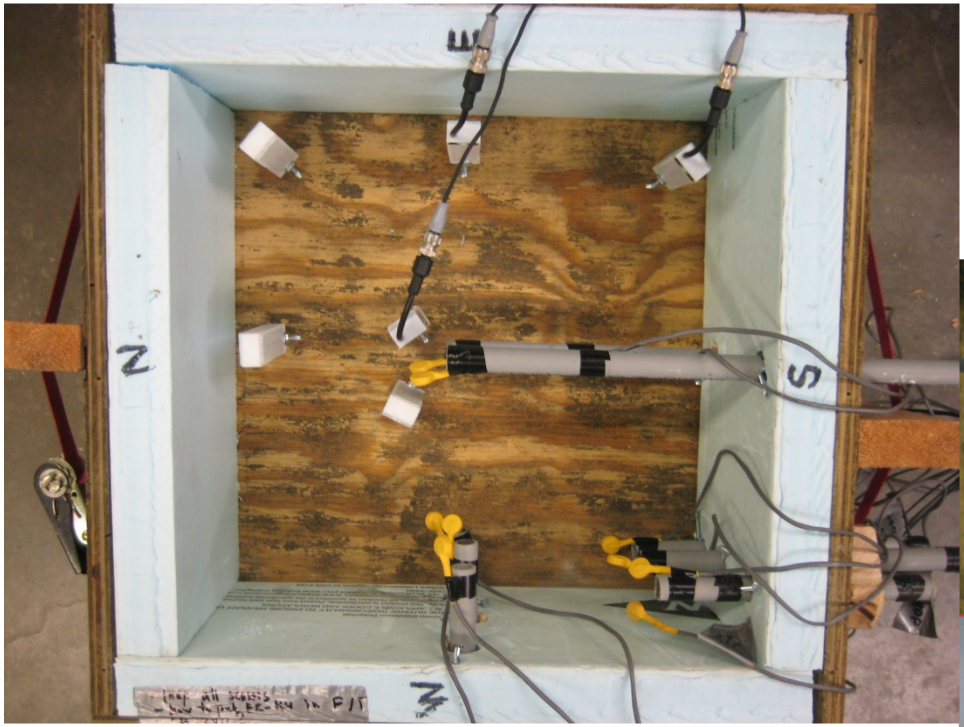
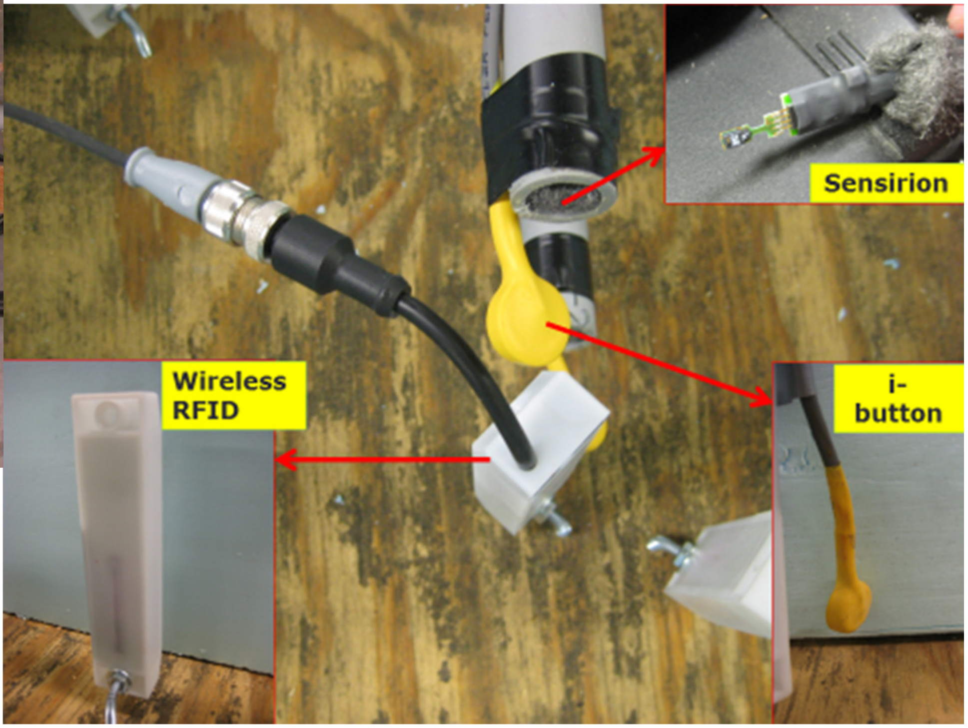
Case Studies at ISU

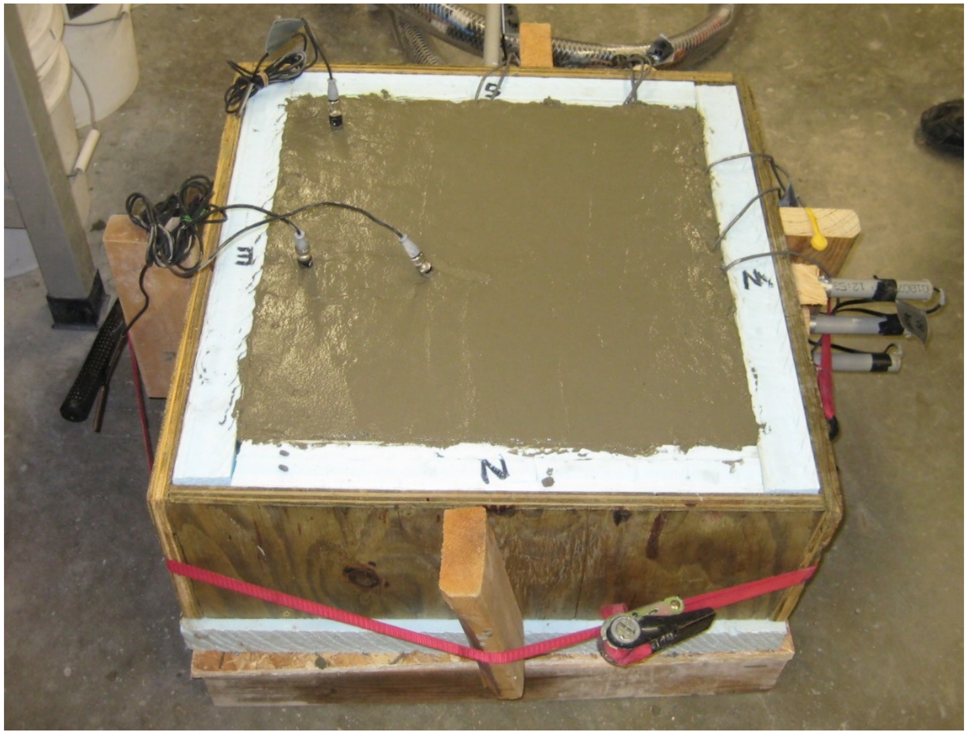
- Laboratory testing of MEMS sensors
- Field testing of MEMS Sensors
- Development of a Wireless MEMS Multifunction Sensor (WMS) system

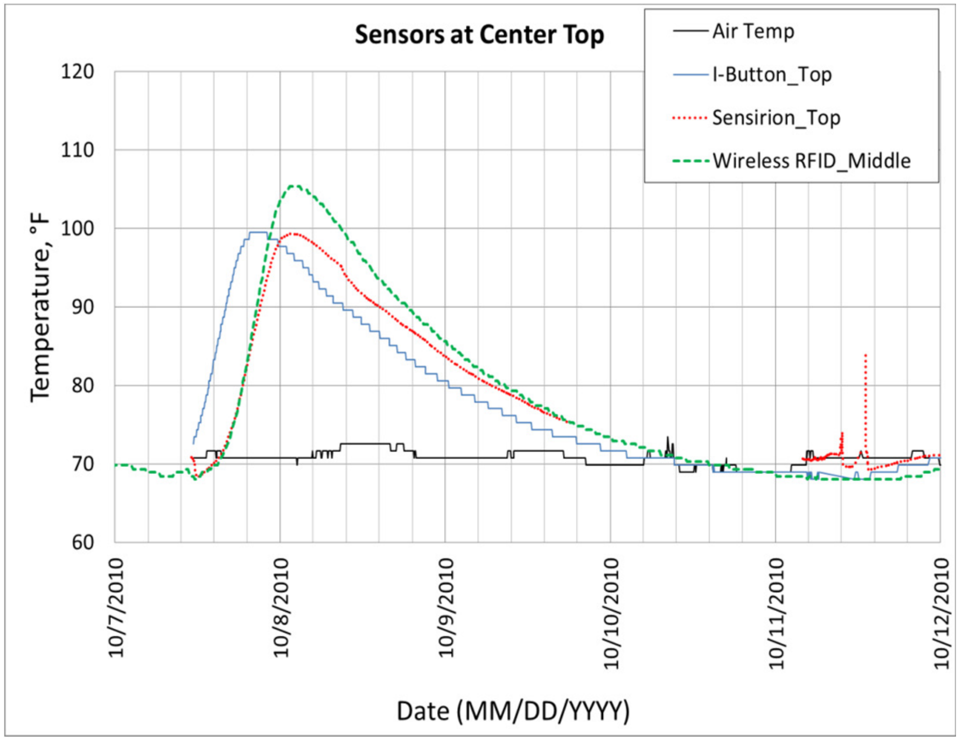
Laboratory Testing of MEMS Sensors





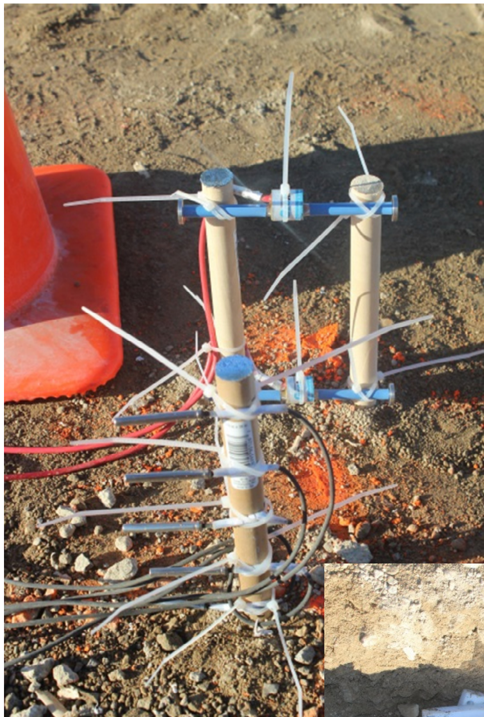
Laboratory Testing of MEMS Sensors





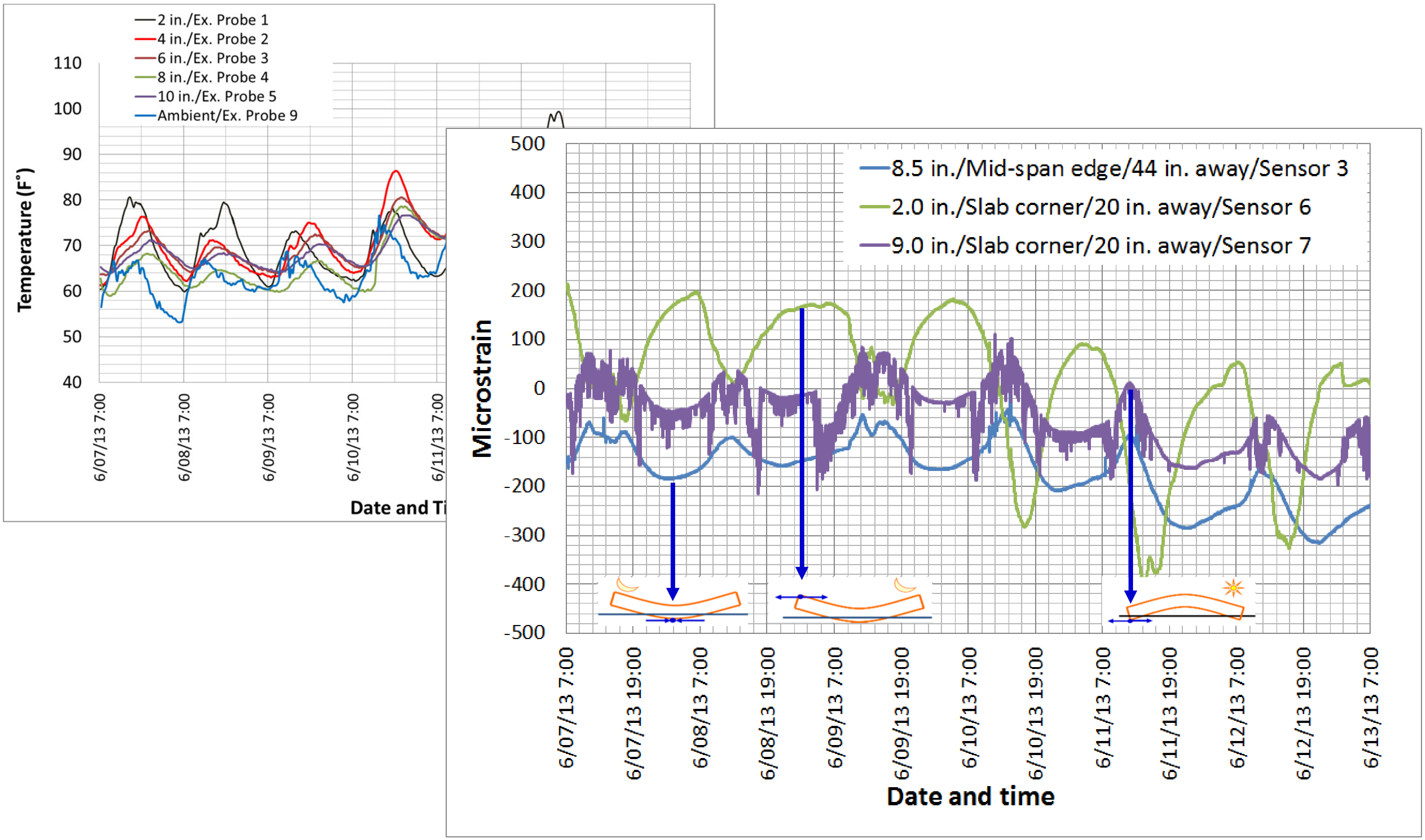
Laboratory Testing of MEMS Sensors

Field Testing of MEMS Sensors: US-30



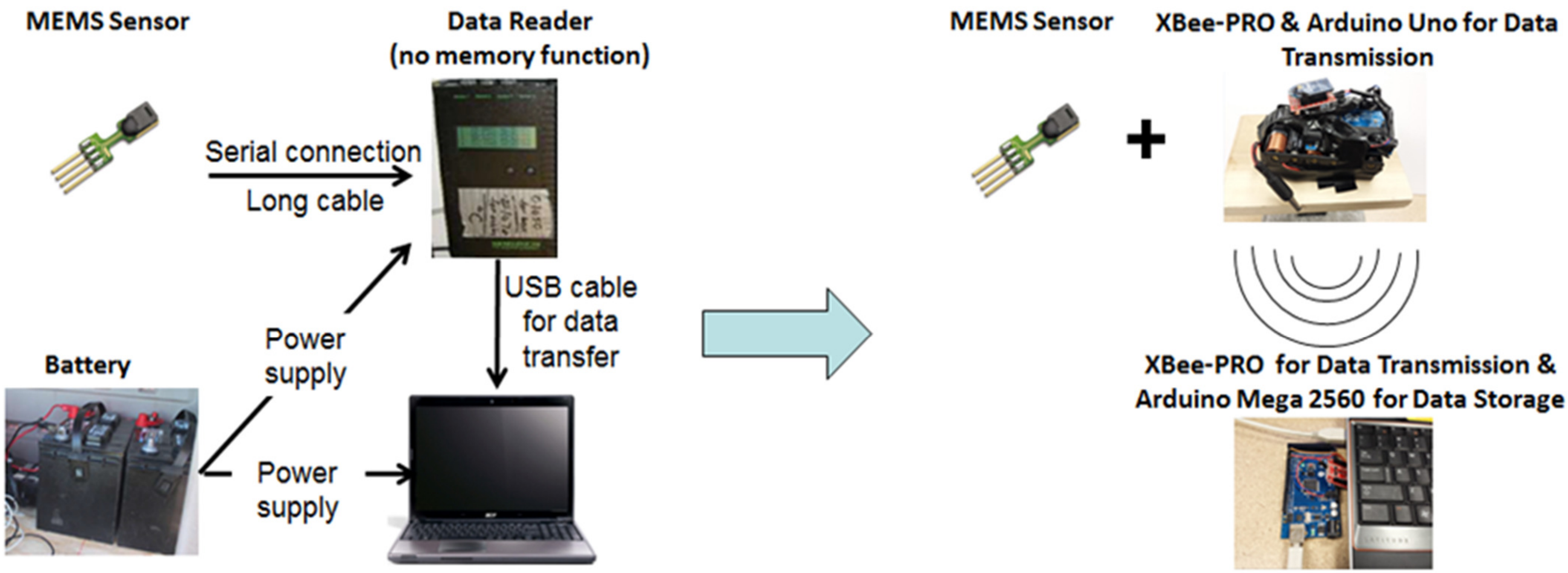

Field Testing of MEMS Sensors: US-30

Field Testing of MEMS Sensors: US-30



Development of WMS System

- Wireless MEMS System Developed at Iowa State University for Monitoring Moisture/RH in Concrete



Wired MEMS system

Implemented wireless MEMS system

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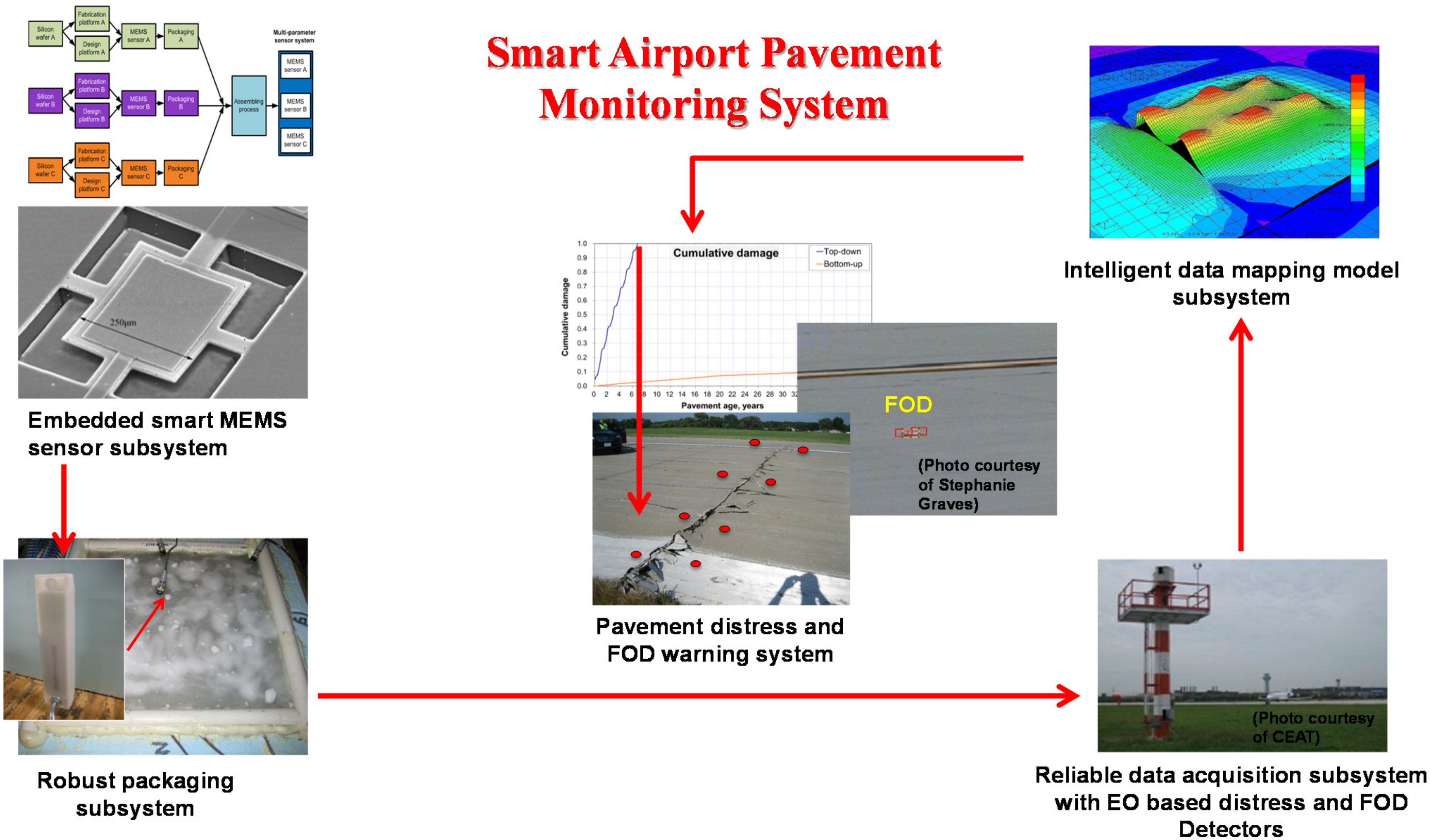
Conceptual Smart Airport Pavement Health Monitoring



Conceptual Smart Airport Pavement Health Monitoring

- Embedded smart MEMS sensor subsystem
  - MEMS system: circuit design, fabrication, and reliability testing
  - Multifunctional: strain, temperature, and moisture
  - Self-energy harvesting (Passive): Piezoelectric materials

Conceptual Smart Airport Pavement Health Monitoring

- Robust package subsystem
  - Protect embedded smart MEMS sensor during installation/construction and under harsh climate and traffic conditions

Conceptual Smart Airport Pavement Health Monitoring

- Reliable data acquisition subsystem with Electro-optical (EO) based distress and FOD detectors
  - Wireless capacity to collect data from sensors by stationary or mobile system
  - Data storage/transfer

Conceptual Smart Airport Pavement Health Monitoring

- Intelligent data mapping model subsystem
  - Data mapping of entire section based on data acquired from sensors buried at specific locations through sensing data fusion and geo-spatial analysis approach
  - Real-time or quasi real-time analysis for continuous health monitoring

Conceptual Smart Airport Pavement Health Monitoring

- Pavement distress prediction system
  - Crack damage prediction and remaining life prediction system to eliminate the need for costly and time consuming material characterization in field and lab
  - Critical crack initiation warning system

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Summary

- Recent advancements in
  - MEMS/NEMS technologies
  - Wireless sensor networks
  - Efficient energy scavenging paradigms
- Opportunities for long-term, continuous, real-time response measurement and health monitoring of airport pavement systems

Summary

- The required properties for health monitoring of airport pavement systems include
  - Multifunction sensing capacity
  - Wireless communications
  - Lower energy consumption for operation
  - Robust packaging
  - Reliable data acquisition
  - Intelligent data mapping
  - Early warning of critical distress initiation

Summary

- Such health monitoring of airport pavement systems is crucial for:
  - Maintaining the structural and functional performance for safe aircraft operations
  - Providing optimal timing of maintenance/rehabilitation activities and efficient allocation of scanty resources
  - Understanding complex pavement system behavior to achieve sustainable airport pavement systems

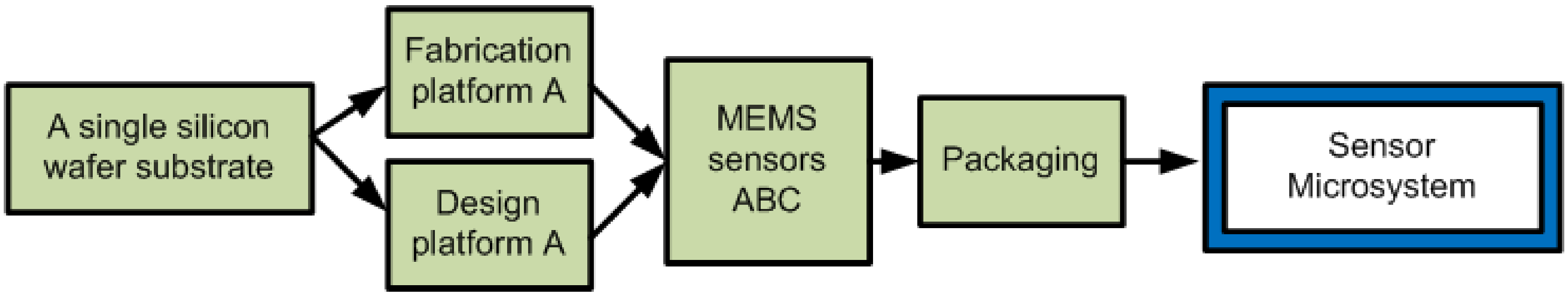
Thank You!

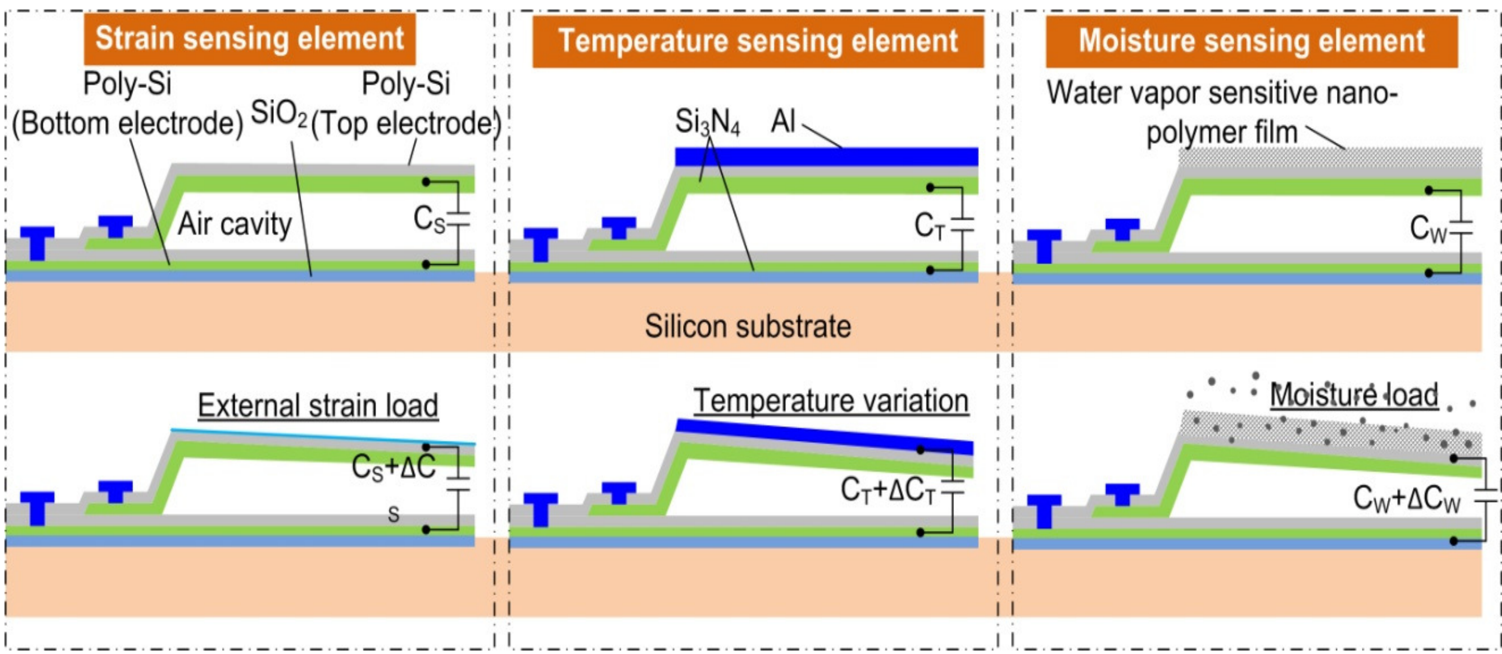
Questions & Comments?

EXTRA SLIDES

Development of Wireless MEMS Multifunction Sensor (WMS) System

Development of a Wireless MEMS Multifunction Sensor (WMS) System



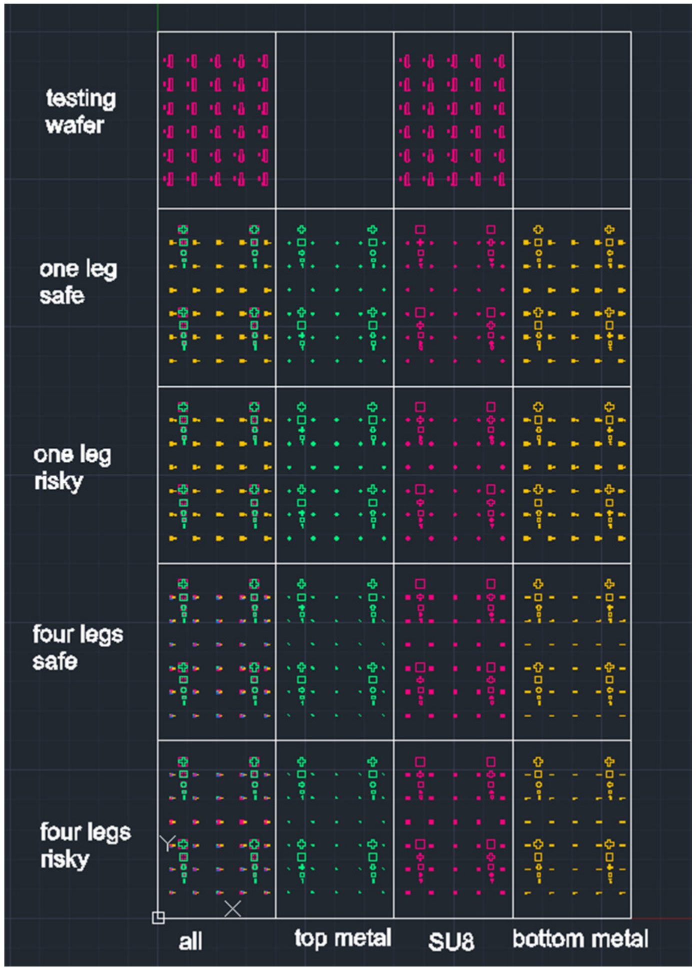


All three sensing elements are integrated on the same substrate

(Photo courtesy of Dr. Liang Dong in ISU)

Development of WMS System

- First generation of MEMS
  - 4 different set of designs
  - One leg and four leg design; each of them have a safe and risky version



(Photo courtesy of Dr. Liang Dong in ISU)

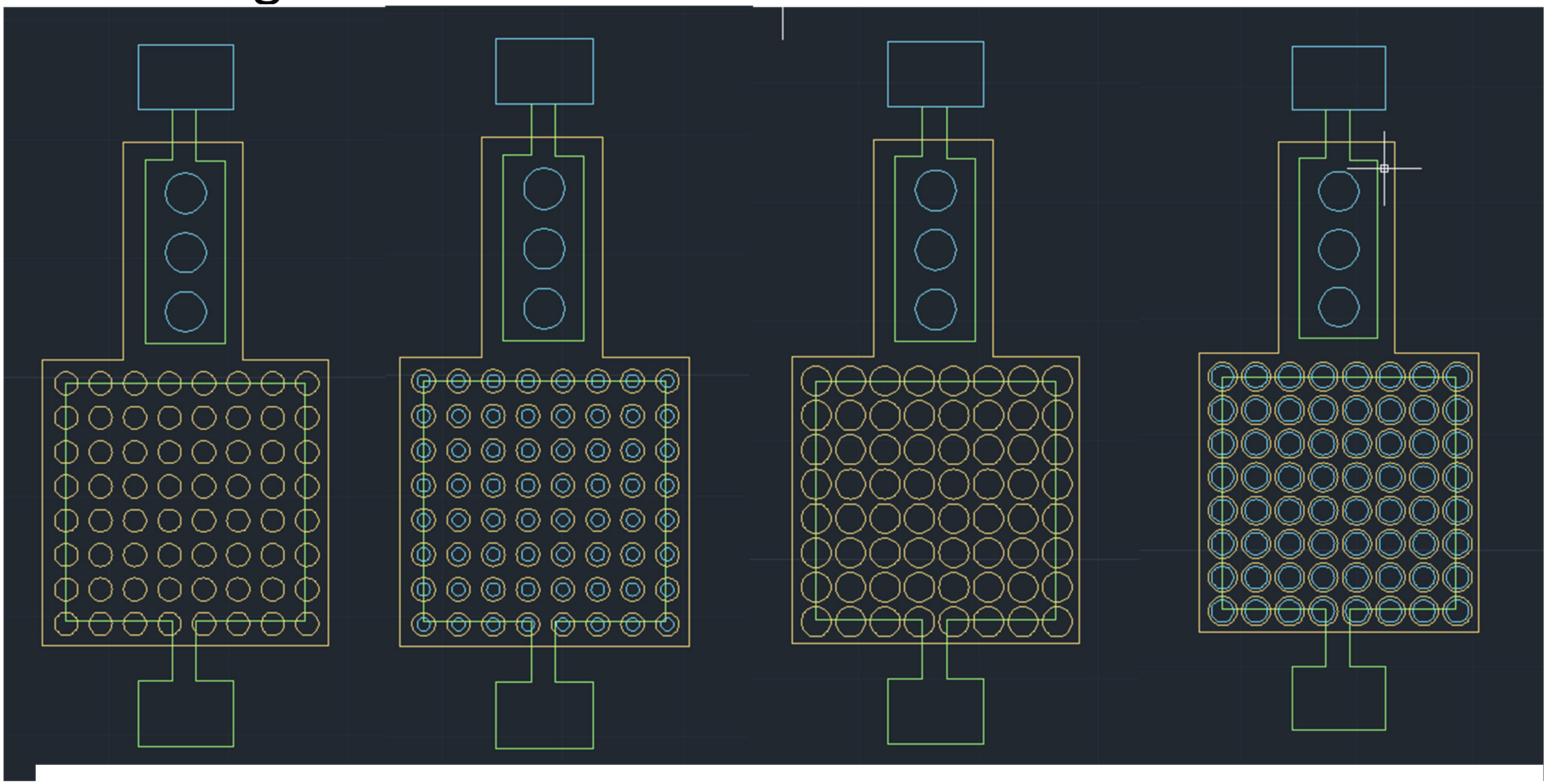
Development of WMS System

- Second generation of MEMS

(Photo courtesy of Dr. Liang Dong in ISU)

Development of WMS System

- Third generation of MEMS



Pic1 Pic2 Pic3 Pic4

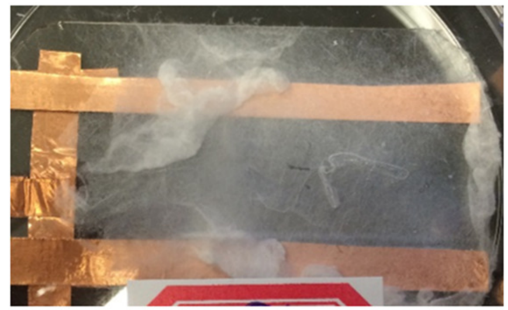
(Photo courtesy of Dr. Liang Dong in ISU)

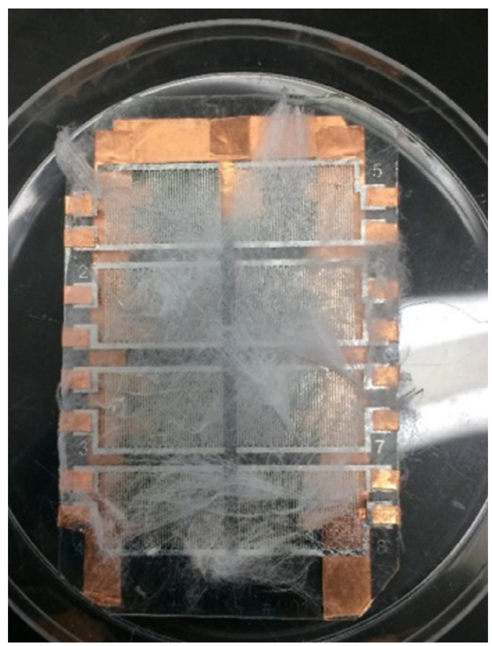
Development of WMS System

- Nanofiber coating MEMS

4%

8%

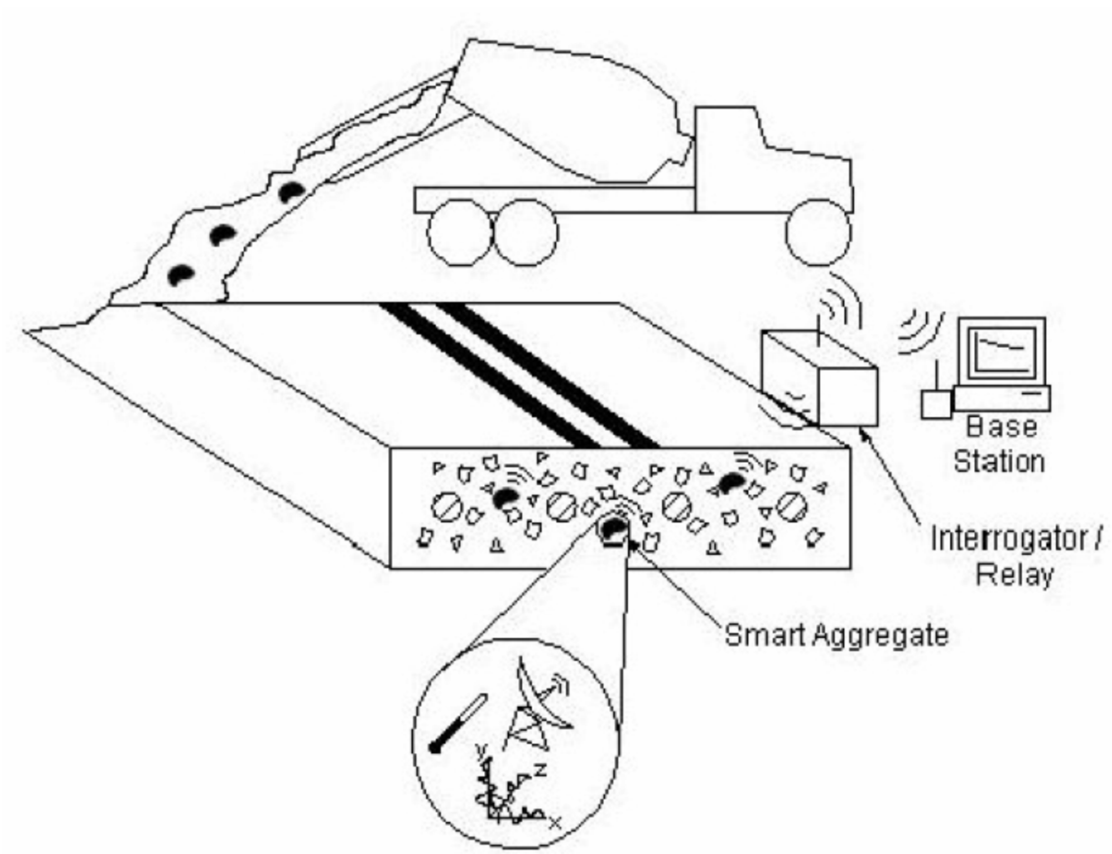




(Photo courtesy of Dr. Liang Dong in ISU)

OTHER EXTAR SLIDES

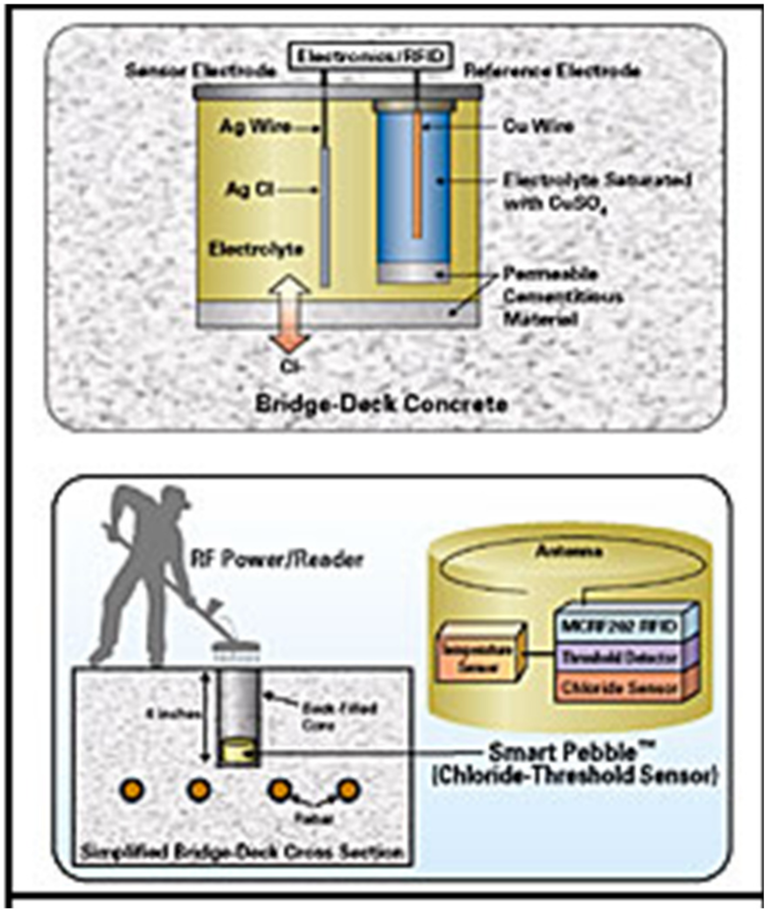
“Smart Aggregate” System



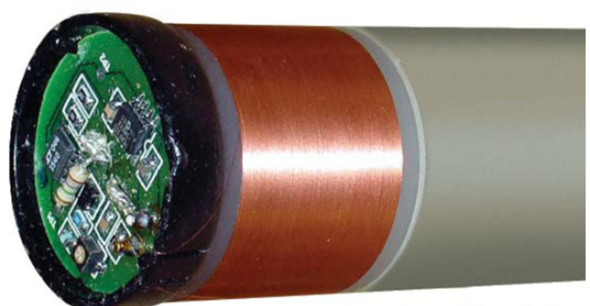
- Carnegie Mellon University
- Approximately 2.5 cm in diameter
- Distributed monitoring of concrete structures

(Sackin et al. 2000)

“Smart Pebble” Concept



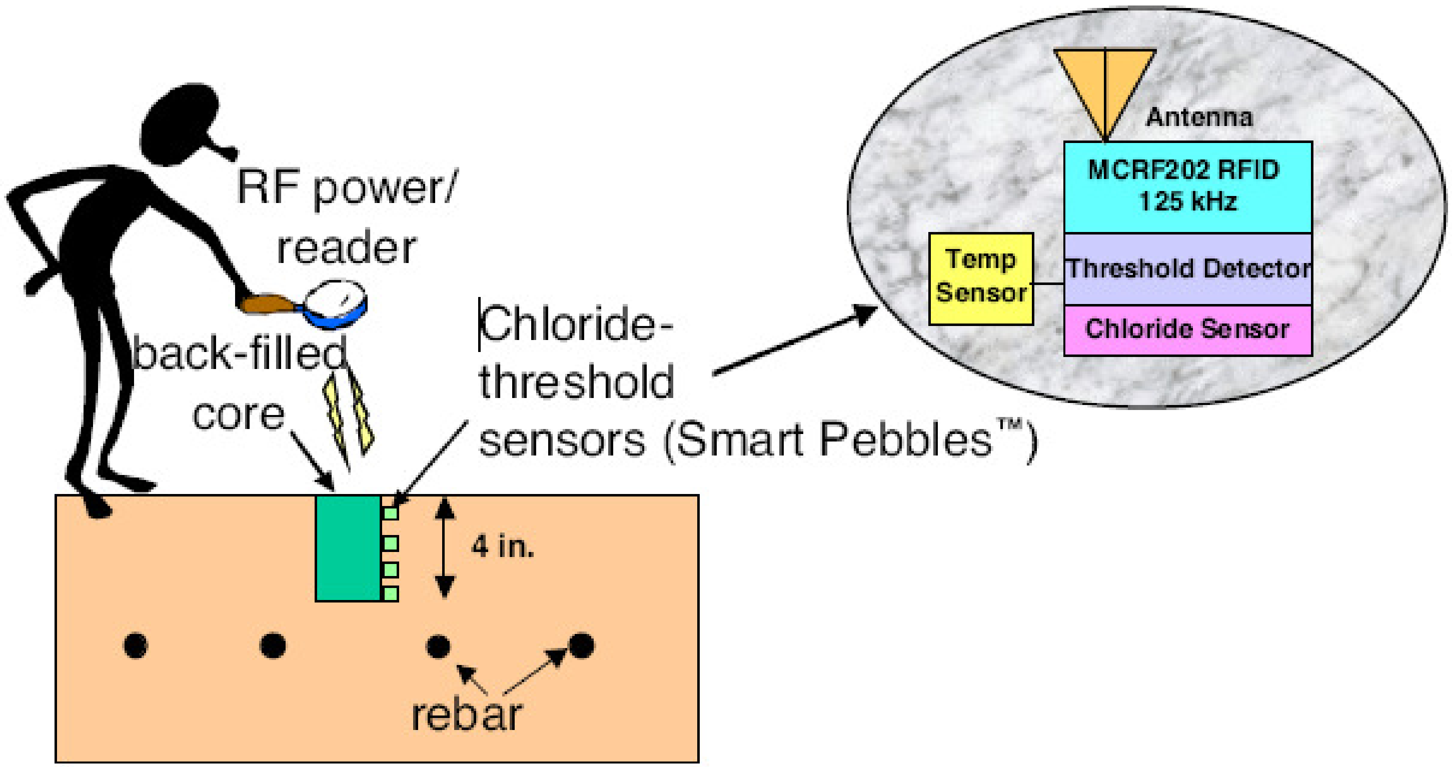
- SRI International, CA
- Size of a piece of gravel
- Chloride sensor
- monitor for the intrusion of rust-inducing salt



This gravel-size “pebble” wirelessly reports on a bridge’s health.

(Watters 2003)

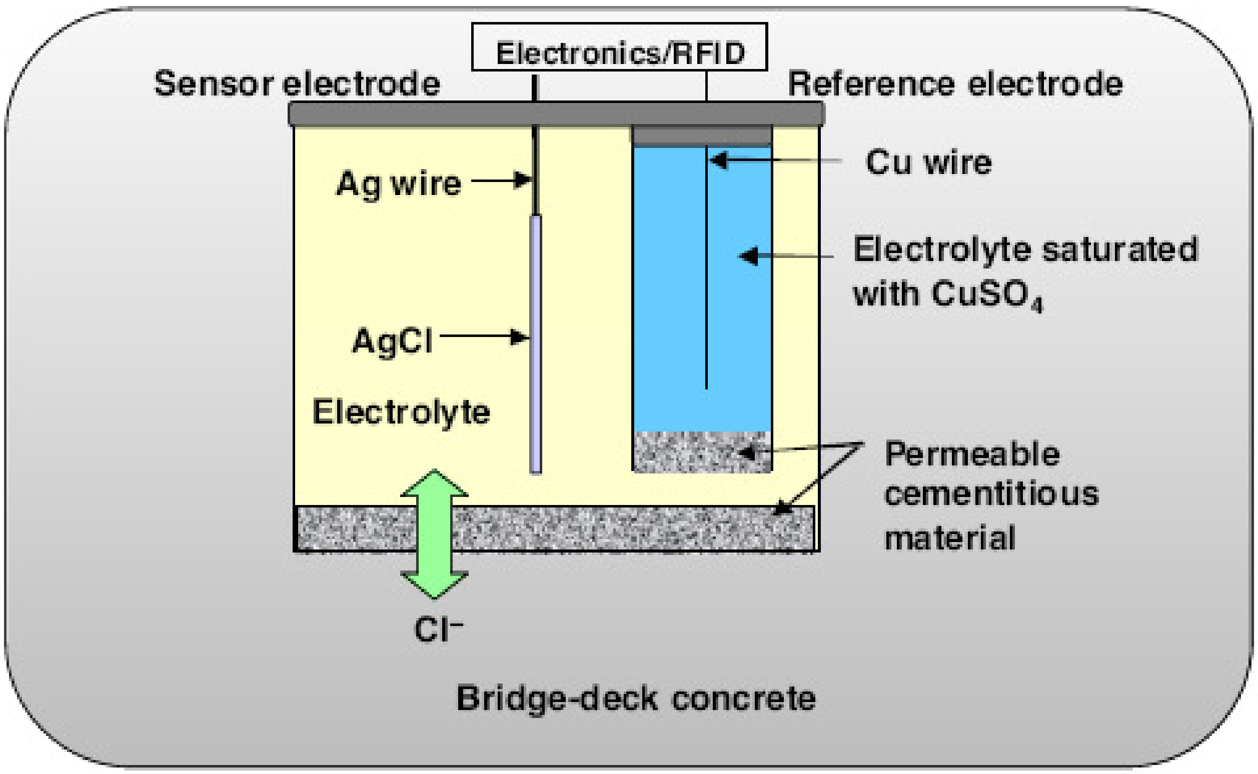
“Smart Pebble” Concept



Simplified Bridge-Deck Cross-Section

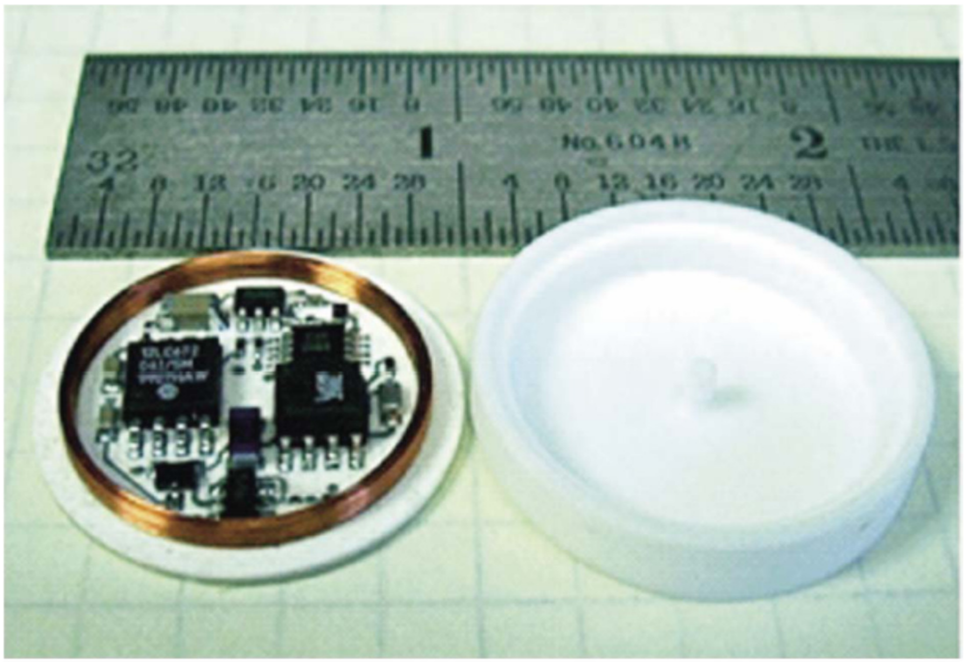
(Watters 2003)

Chloride Sensor Concept



(Watters 2003)

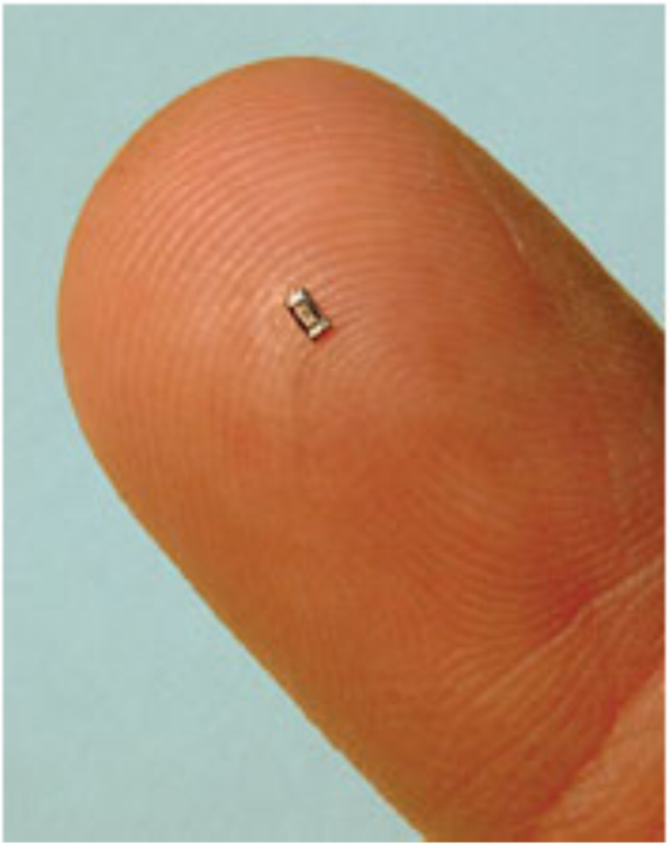
John Hopkins “Smart Aggregate”



- Wireless Embedded Sensor Platform (WESP)
- Corrosion of rebars
- Environmental monitoring of chemical and biological agents
- Powered by a remote transmitter

Darrin et al (2004)

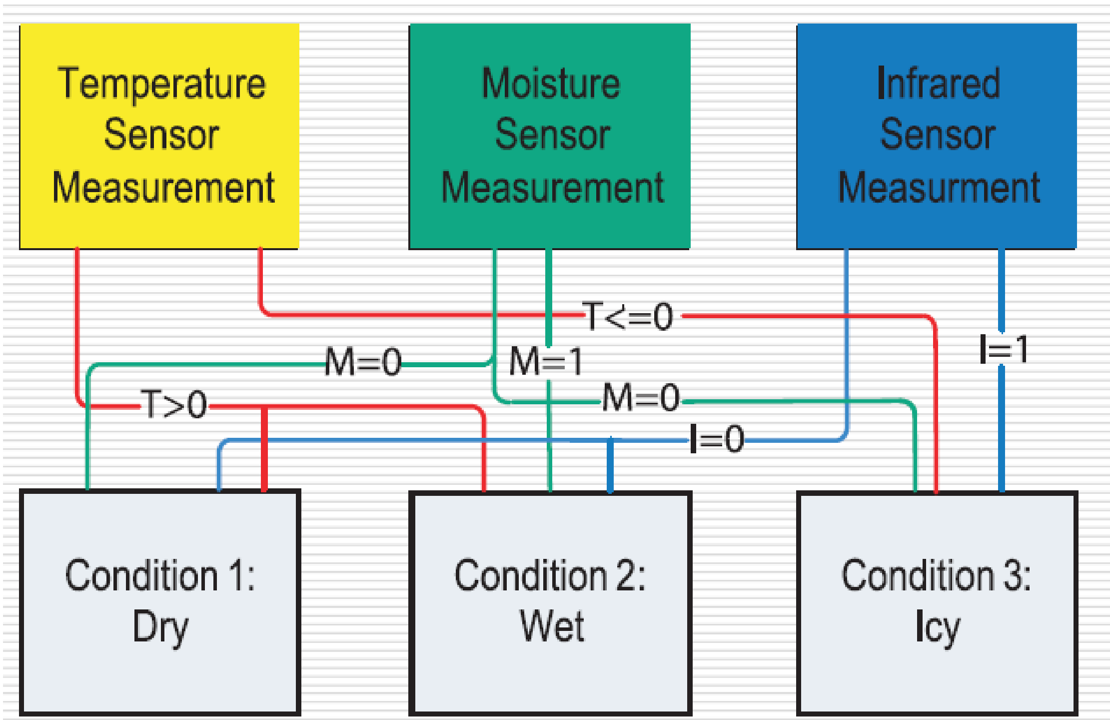
MEMS Concrete Monitoring System



Advanced Design Consulting USA, Inc

- Radio-Frequency Identification Devices (RFIDs) + MEMS
- Monitor temperature, moisture, pH, conc. of Cl, Na, K ions
- Provide critical data for evaluating concrete performance right from freshly mixed stage to repair stage

Monitoring Pavement Condition using "Smart Dust"

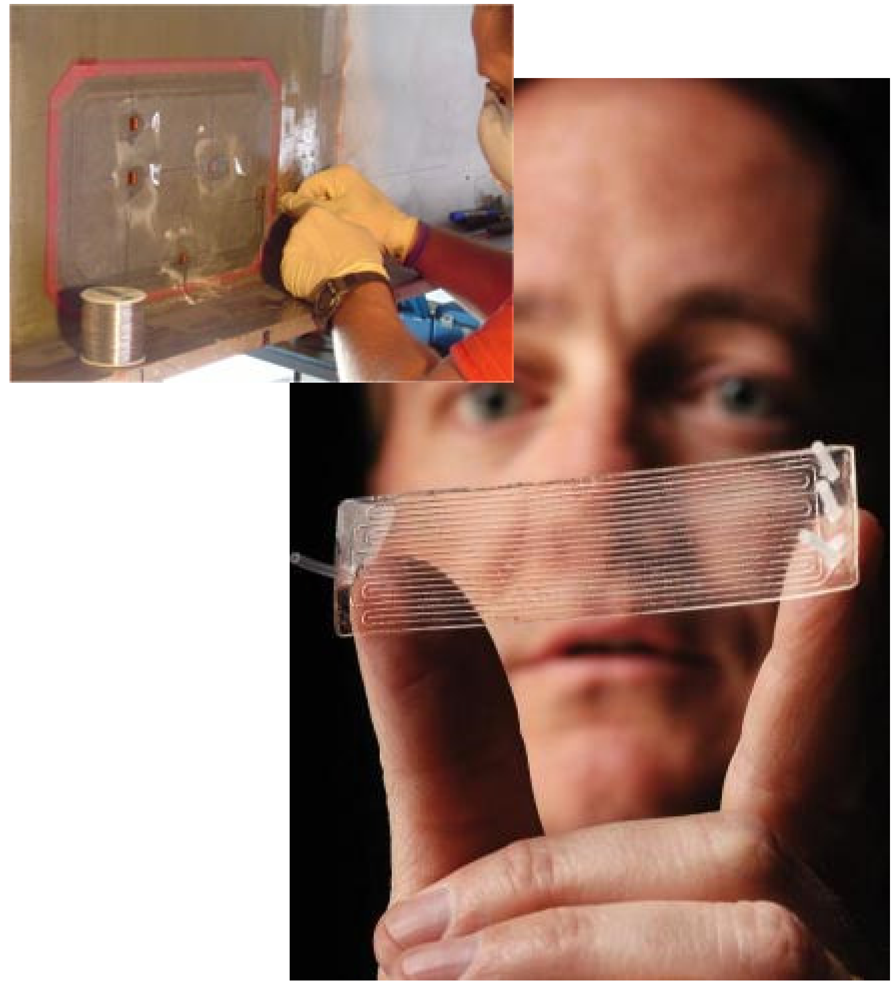


"Smart Dust" sensor network for monitoring pavement temperature and moisture presence to detect icy road condition

(Ferzli et al. 2006)

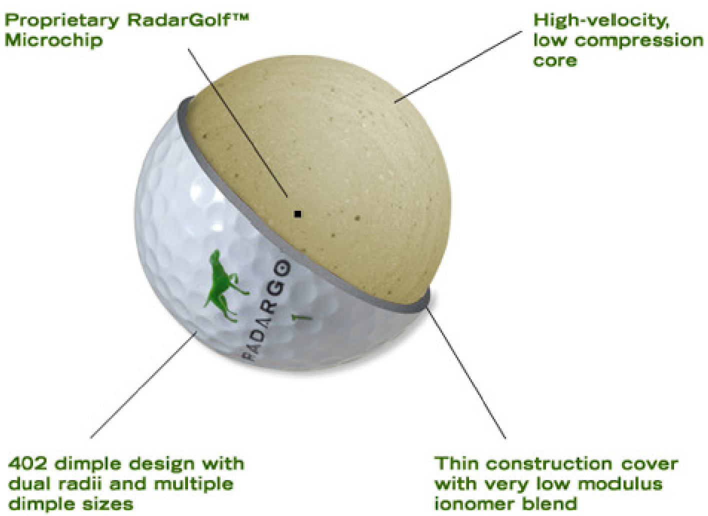
Comparative Vacuum Monitoring (CVM) Device

- Full-time SHM sensors
- Networks of permanently mounted sensors can detect
  - Hidden cracks
  - Erosion
  - Impact damage
  - Corrosion

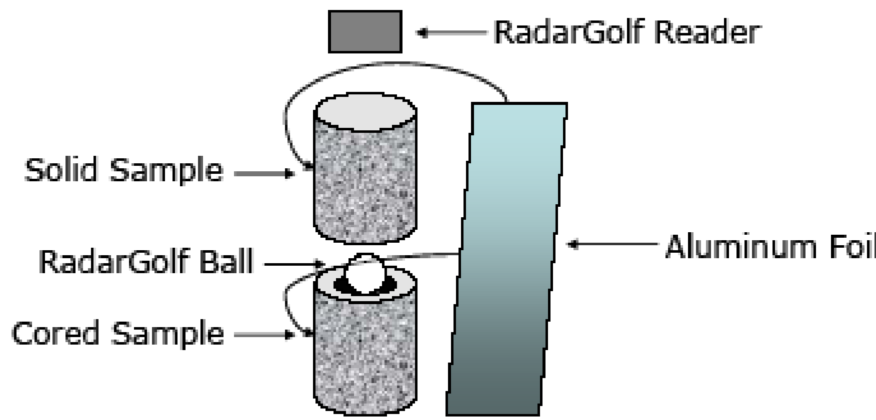


(Sandia National Labs 2007)

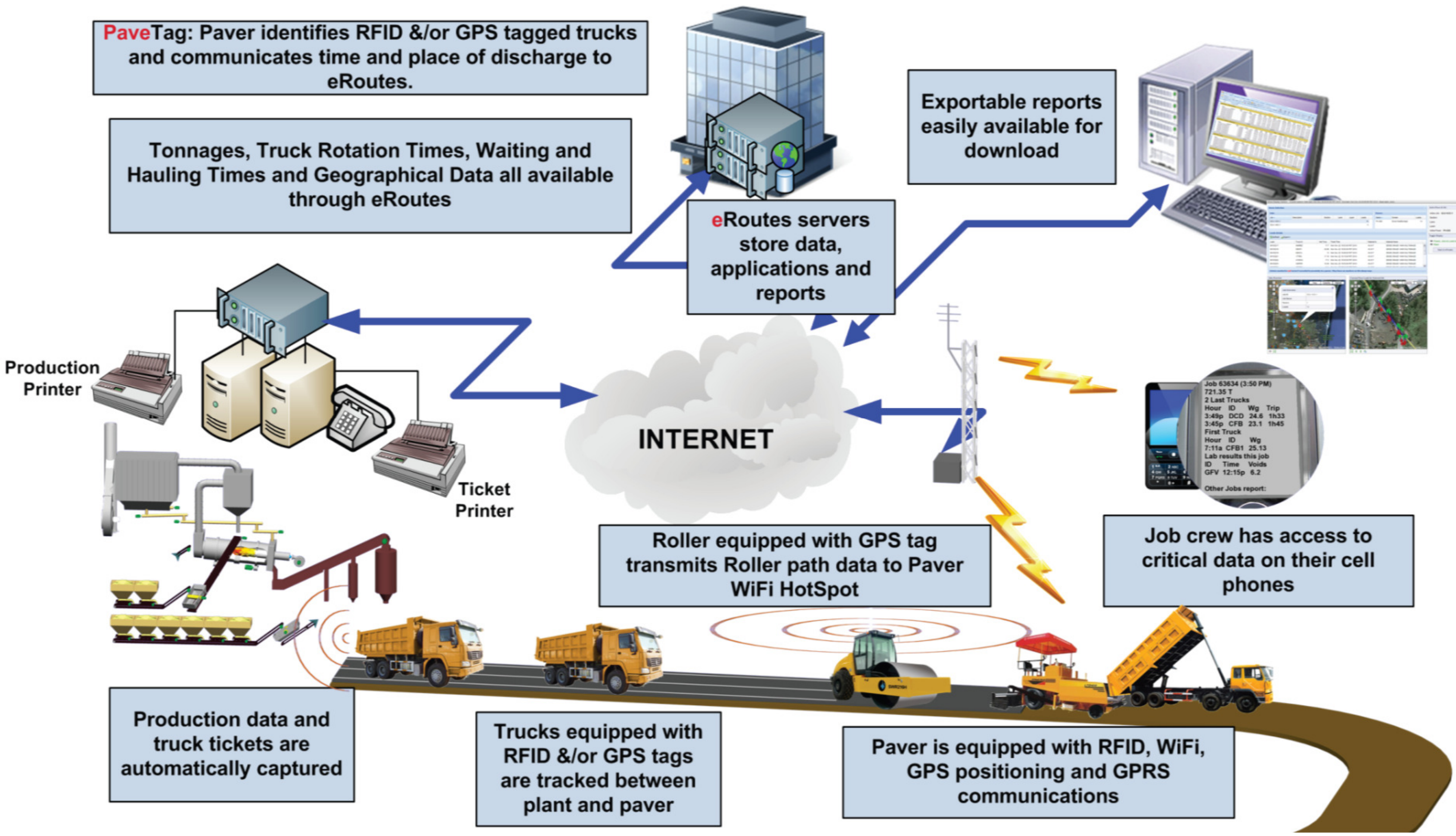
RFID Asphalt Material Tracking System



Evaluating RFID signal attenuation through asphalt (Schwartz, 2007)

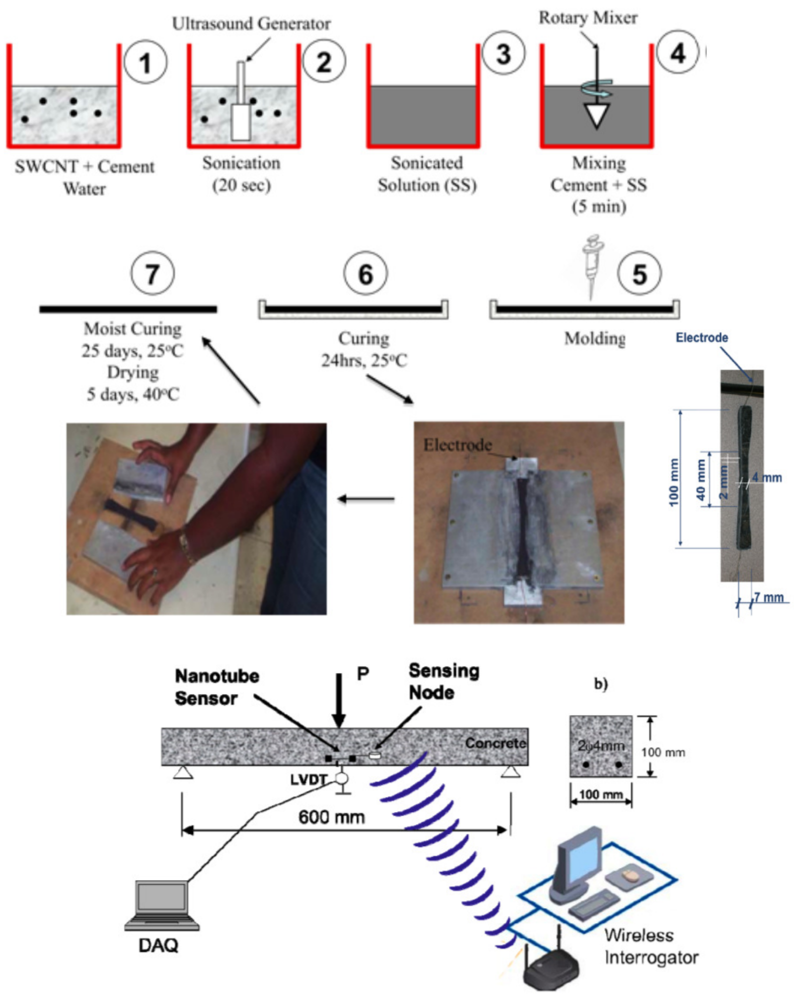


HMA Real-time Tracking Using RFID



Courtesy: Minds, Inc.

Wireless Nanotube Composite Sensor for Concrete Crack Detection



- Cement CNT-sensors
  - Portland Cement
  - Untreated Single-Walled Nanotubes (SWNT)
  - Thin Copper Electrodes
- Off-the-shelf low-cost wireless communication system

Saafi and Kaabi (2009)

Introduction

- Airport pavement distresses in Tribhuvan International Airport in Kathmandu, Nepal
  - Rutting and potholes were observed in flexible pavement during hot summer in 2013
  - A number of international flights were delayed, diverted and cancelled
  - Runway were closed which not only delivered a negative message to other countries but also caused a huge loss on Nepalese tourism business.

(Nepal, 2014)

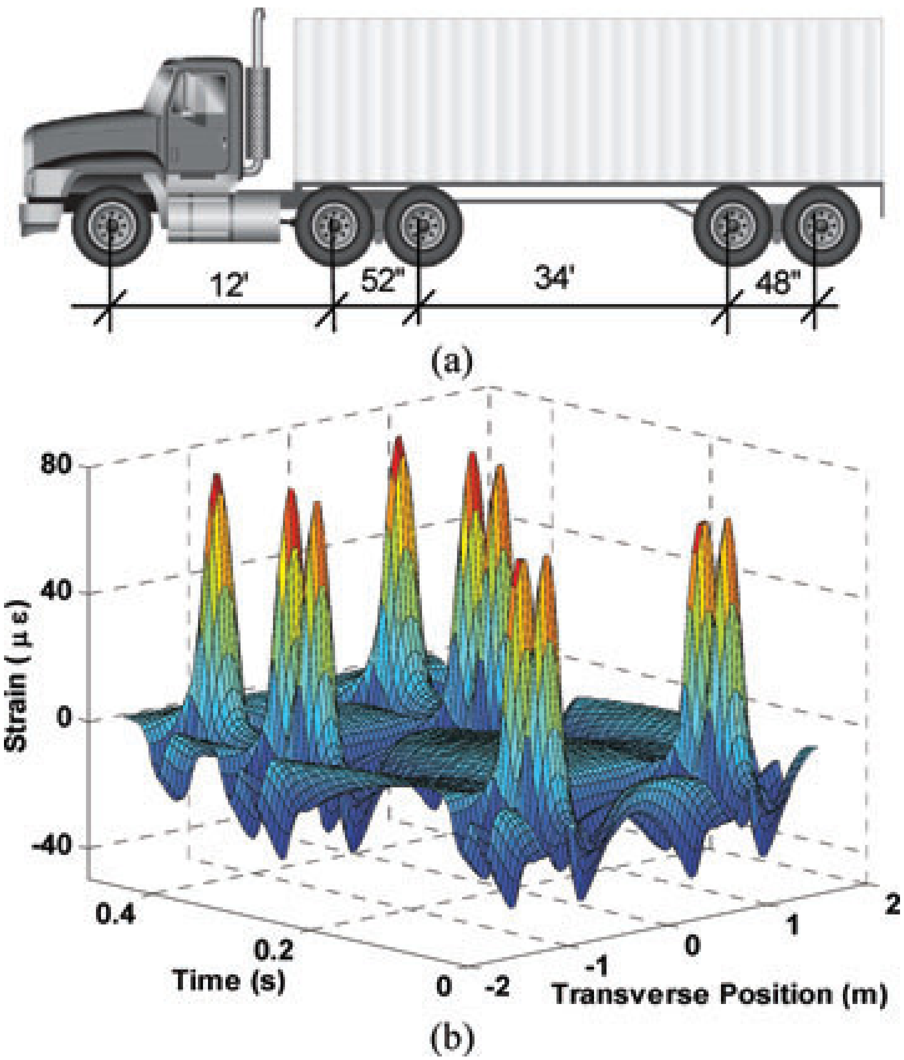
Health Monitoring of Airport System

- How to Conduct Health Monitoring of Airport Pavement Systems?
  - Micro-Electromechanical Systems (MEMS)/ Nano-Electromechanical Systems (NEMS) Technologies Based Sensors
    - Radio-Frequency Identification (RFID) tag
    - Multifunction sensor
  - Electro-optical (EO) Sensing
    - iFerret system (Chicago O'Hare International Airport)
  - Wireless Network
    - Challenge to airport pavement monitoring is signal disturbance to airplane

Smart Pavement Monitoring System

Example of a truck (class 9) used for strain response data generation,

Example of longitudinal strain profile evaluated at the bottom of the HMA layer for a moving load induced by a class 9 truck.



Self-powered piezo-floating-gate array

Lajnef et al. (2011)

Health Monitoring of Pavements: Examples

- Runway Instrumentation at Denver International Airport (DIA) in 1990s
  - 460 sensors of strain gages, Thermocouples, and Time Domain Reflectometrs were instrumented in 16 slabs
  - Data acquisition system (DAS) was placed in-situ

- Optical Fiber Sensors in Chiang-Kai-Shek International Airport (CKS) in 2002
  - Dynamic and static strain gages were used to monitor joint movement and thermal stress
  - Smartec SOFO optical fiber sensors (static strain gage) were used to measure concrete joint movements (expansion and contraction)

Health Monitoring of Pavements: Examples

- Piezoelectric Strain Sensor for Smart Asphalt Pavement Monitoring in 2013
  - Wireless piezoelectric strain sensor system was investigated by Lajnef et al. to estimate fatigue damage for asphalt pavements in 2013
  - A RF reader mounted on a moving vehicle could be used to read and download the data from the sensor as well

(Lajnef et al. 2013)